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CRYOGENIC MONOCRYSTALLINE OPTICAL CAVITY FOR LASER STABILIZATION AND PRECISE TIME MEASUREMENTS

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Objectives

The overall objective of this project was to conduct research toward the stabilization of the frequency of a laser to one part in 10^{18} by locking it to a resonance of a cryogenic Fabry-Perot optical cavity. The mirror spacer of this cavity is a high quality monocrystal maintained at cryogenic temperatures. This required three intermediate objectives: (1) The laser would track the cavity resonance with an error of 0.1 $\mathrm{Hz}/\sqrt{\mathrm{Hz}}$ for fluctuations below 10 mHz. (2) The thermal expansivity of this crystal would be low enough at a temperature of 1 K, i.e. 10^{-12}/K, so that temperature regulation of 1 μK would allow a cavity length stability at the required 10^{-18} level. (3) The cavity would be suspended in its cryogenic vacuum chamber so that mechanical vibrations would not perturb its length, and hence its resonant frequency, beyond the required level.

Results

With regard to these intermediate objectives, good results were obtained with the first, but more research is needed with regard to the other two.

During this project, two lasers were used: a He-Ne gas discharge laser of 0.633 μm wavelength, and a diode-pumped Nd:YAG laser at 1.06 μm. Best results were obtained with the Nd:YAG. Placing this laser in a hermetically sealed chamber and locking it to the reference cavity on an optical table at room temperature produced a tracking error of 0.64 $\mathrm{Hz}/\sqrt{\mathrm{Hz}}$ below 10 mHz. The mirror finesse was 450 in these initial experiments, and 18 μW of power was incident on the maximum-detecting photodiode. Stabilization at the 10^{-18} level would require a finesse of $\sim 20,000$ which can be obtained.

The cavity spacer consisted of a monocrystalline silicon cylinder 15 cm in length and 7.5 cm in diameter. A 1.2 cm diameter hole was bored along the axis for passage of the light beam. The mirrors were press-fit against the end faces of the spacer by metal shim springs attached to aluminum mounting collars. Each collar was in turn held against the silicon end face by a pressure plate attached to the cavity suspension frame. This frame and a previous version of the cavity where the mounting collars were glued on has been described elsewhere.[1]

The cavity was mounted into the cryostat vacuum chamber, and two attempts were made to operate the stabilized laser with the cavity at 4 K. Both were unsuccessful. The first attempt failed when the cavity went out of alignment at a temperature of $\sim$ 100 K. Alignment relies on the line-of-sight positioning of optical components, and the beam line includes two right-angle bends in the low-temperature part of the apparatus.

The cavity was re-aligned and re-cooled, and the alignment remained intact. That experiment revealed the need for more acoustic isolation. Figure (1) shows the effect of the bubbling of the cryogenic bath on the cavity transmission peaks. Even though the servo control was capable of locking on such peaks in the midst of all the jitter, the frequency was controlled only to within the $\sim$ 3 MHz bandwidth of the resonance. We also conclude that the pressure-plate method for attaching the mirror mounting collars contributed to noise pickup. We were thus unable to make a new measurement of the thermal expansion coefficient of the cavity. A previous measurement of that quantity using glued mounting collars was higher than expected.[2] Lower noise levels will be obtained with improved acoustic isolation and optical contact between the mirrors and cavity spacer.

Finally, we confirmed a small decrease in the mirror finesse at cryogenic temperature. In this case the finesse at 100 K was found to be 270.

Recommendations

Our idea of locking a laser to a cryogenic cavity is now copied in Australia and Japan. To further our own progress, we have identified a number of areas in which improvements are needed and would be straightforward:

- *Fiber-optic coupling to the cavity.* Optical fibers have been tested successfully in coupling cryogenic high-finesse cavities to a He-Ne laser at room temperature. This would solve the problem of beam misalignment while the cavity is cooling.

- *Matched-substrate mirrors.* The aluminum mounting collars were problematic in two ways. When glued on, the expansivity of the cavity was too high. When pressed on, the cavity was susceptible to vibrations. Both of these problems can be circum-

vented by using a cavity spacer and mirror substrates made out of the same high-quality monocrystal. Sapphire is a good candidate substance as it is transparent in the appropriate wavelengths, has an acceptably low thermal expansivity, and is readily available in monocrystalline form. The cavity end faces and mirror substrate contact surfaces could be polished optically flat, and then joined by optical contact to make a complete cavity.

These improvements, in conjunction with the demonstrated tracking ability and a proper cavity suspension, would bring about a significant milestone toward achieving our main design goal.

References

1. J.-P. Richard and J.J. Hamilton, *Rev. Sci. Instrum.* **62**, 2375 (1991).
2. J.J. Hamilton and J.-P. Richard, "Low Temperature Thermal Expansion of Boron-Doped Silicon Monocrystal," University of Maryland Physics Department Technical Report No. PP 92-218 (unpublished).

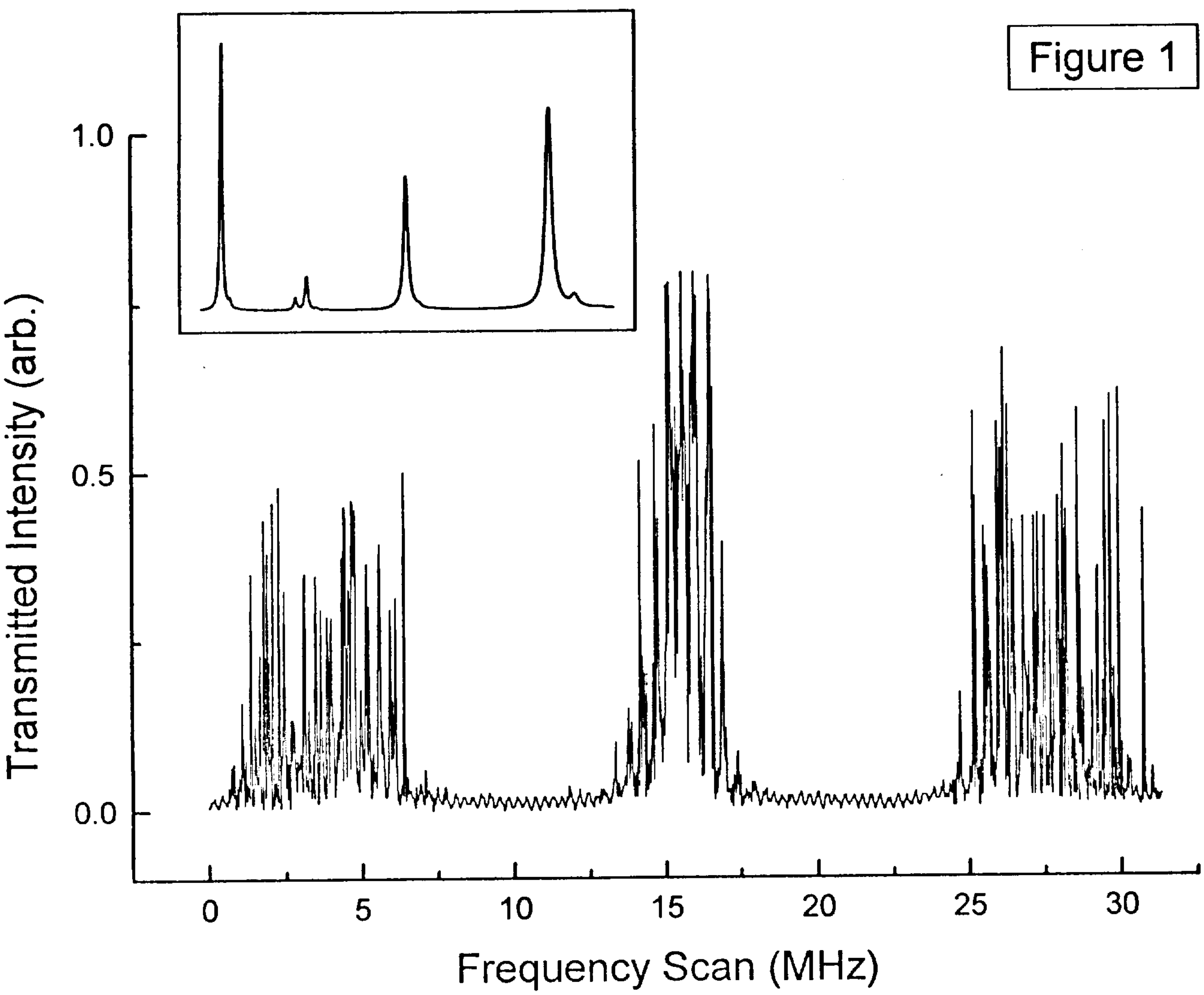

Figure 1: Cavity transmission peaks in the presence of a cryogenic bath. Bubbling of the bath produces jitter noise in the peaks. Compare the smooth peaks obtained at room temperature (inset). Laser stabilization is obtained when the servo electronics lock the laser frequency to the center of one peak. In the midst of the vibrational noise, the ability of the electronics to determine the peak center was hampered, and lower stabilization resulted.